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Assessment of the Diaphragm Condition For The Floor Systems

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Abstract - *Construction technologies are developed to primarily satisfy the needs of a more economic, faster and more efficient building industry; as a result, a wide variety of structural options for floor systems used in the building. Structural solutions have been developed to satisfy the primary function of a floor system, which is to resist and distribute efficiently the vertical loads within the structure. In most of the studies, the diaphragm condition is assumed as rigid, but this can affect the integrity of the buildings. There are available analytical and experimental research studies that evaluate the diaphragm condition under lateral loading for some floors systems. Such studies are limited to some storey level. This study investigates the diaphragm condition for the different types of floor systems for the office building. The influence of aspect ratio and height of the building on the behavior of the diaphragm is also determined. The study of diaphragm condition is important in order to help improve professional practice and help reduce the vulnerability of the new inventory of structures. The diaphragm condition varies depending on the aspect ratio and height of the building for the different floor systems. The building with smaller aspect ratio and height has better diaphragm condition for the floor systems considered in both the static and dynamic analysis.*

Key Words: **Floor Systems, Diaphragm, Aspect Ratio, Flexibility Index**

1. INTRODUCTION

There is a wide variety of structural options for floor systems used in buildings today as the construction technologies are developed to primarily satisfy the needs for more economic, faster and more efficient building industry. Many of the structural solutions have been developed to satisfy the primary function of a floor system, which is to resist and distribute efficiently the vertical loads within the structure. Assuming that floor systems behave as rigid and strong diaphragms under lateral loading without studies can seriously compromise the integrity of buildings [1].

The diaphragm is a horizontal system (roof, floor or other membrane or horizontal bracing) acting to transmit lateral forces to vertical resisting elements. The floors and roof of a building, that help in resisting gravity loads, are also generally designed to act as diaphragms. In this respect, they are required both to distribute seismic forces to the main elements of horizontal resistance, such as frames and shear walls and to tie the structure together so that it acts as a single entity during an earthquake. The robustness and redundancy of a structure is dependent on the performance of the diaphragms.

There are three types of the diaphragm in structural modelling:

Rigid diaphragm: It represents a plane of very high rigidity. They distribute loads to elements which connect to them based on the stiffness of elements. They achieve this by tying all the joints within the plane of diaphragm together for both translation and rotation. Also, the diaphragm may be considered rigid when its midpoint displacement under lateral load is less than twice the average displacements at its ends.

Semi - Rigid diaphragm: They distribute load based on both the stiffness of the elements which connect to it and on the stiffness of diaphragm itself. They are those which have significant deflection under load but which also have sufficient stiffness to distribute a portion of their load to vertical elements in proportion to their rigidities of the vertical resisting elements

Flexible diaphragm: They distribute loads to elements which connect to them based on the tributary area of the element within the plane of the diaphragm. A diaphragm may be considered flexible when its midpoint displacement under lateral load exceeds twice the average displacement of the end supports. It is assumed here that the relative stiffness of these non-yielding end supports is very great compared to that of the diaphragm.

Waffle slab system: Waffle slab consists of two directional reinforcement between column heads on the outside of the material which gives the shape of the pockets on a waffle. This type of reinforcement is common on concrete, wood and metal construction. It gives a substance significantly more structural stability without using a lot of additional material. It is perfect for a large flat areas like foundations or floors. They are used in the areas where less number of columns are provided. This form of construction is used in airports, parking garages, commercial and industrial buildings, bridges, residences and other structures requiring extra stability. Waffle slab holds a greater amount of load compared with conventional concrete slabs. Waffle slab tends to be deeper than equivalent ribbed slab system. Fig -1 shows an example for waffle slab system.

Fig -1: Waffle slab system

Ribbed slab system: Ribbed slab consists of wide beams running between columns with narrow ribs spanning in orthogonal directions. Ribbed floors consisting of equally spaced ribs are usually supported by columns. Ribbed slabs are suitable for medium to heavy load conditions. They can span reasonable distances. They are very stiff and particularly suitable where the soffit is exposed. The advantage is on the saving on weight and materials, vertical penetration between ribs are easy, economical when reusable formwork pans are used etc. Fig-2 shows an example for ribbed slab system. Ribbed and waffle slab provide a lighter and stiffer slab compared to that of an equivalent flat slab.

Fig -2: Ribbed slab system

1.1 Objectives of the project

The objectives of the project are:

- To determine the diaphragm condition (rigid, flexible and semi-rigid) of the structure by considering different floor systems.
- To determine the change in maximum storey displacement values of the structures by considering both static and dynamic analysis.
- The determine the change in diaphragm condition with respect to the aspect ratio and the height of the building.

1.2 Scope of the Project

The scope of this study can be specified as:

- Type of floor system is limited to waffle slab system and ribbed slab system.
- Aspect ratios considered are 1, 2 and 3.
- Number of stories considered are 4, 7 and 10.

2. METHODOLOGY

The assessment of floor system of the structures can be performed by the following methods:

- Experimental method
- Using softwares
- By manual calculations

Experiment method can be conducted by carrying out seismic load test on different floor system of the structure. Information on the stiffness, drift, energy dissipation capacity, ultimate strength, and lateral displacement ductility of the floor system can be obtained from such methods. But further complex calculation needed to be carried out for finding more about the diaphragm conditions. The softwares that can be used are SAP2000, ETABS and ANSYS. The use of manual calculations is very tedious for complex structures. ETABS software is used for both the modelling and analysis of the building models.

The following is the methodology used for the project.

- Modelling of buildings (office building) with different types of floor systems considering different aspect ratio.
- Material properties and member properties are defined and assigned to the model.
- The base of the models is fixed for simplicity.
- Loads are assigned to the building structure.
- Linear static and dynamic analysis of the building structure is carried out.
- The values of storey displacement and base shear are to be determined.
- Modelling of the building with rigid diaphragm condition for the different types of buildings for comparison purposes.
- Flexibility indexes are to be calculated.
- Classification of diaphragm condition for the floor system.

3. MODELLING OF THE BUILDING

Symmetrical office building, having floors of height 3.5m is selected as a model for the study. The properties of the building selected for the study is given in Table-1. The models selected for the study are:

Building with waffle slab system and building with ribbed slab system with and without diaphragm condition

- Aspect ratio 1 and number of storeys 4
- Aspect ratio 1 and number of storeys 7
- Aspect ratio 1 and number of storeys 10
- Aspect ratio 2 and number of storeys 4
- Aspect ratio 2 and number of storeys 7
- Aspect ratio 2 and number of storeys 10

- Aspect ratio 3 and number of storeys 4
- Aspect ratio 3 and number of storeys 7
- Aspect ratio 3 and number of storeys 10

Building with ordinary slab system

- Aspect ratio 1 and number of storeys 4
- Aspect ratio 1 and number of storeys 7
- Aspect ratio 1 and number of storeys 10
- Aspect ratio 2 and number of storeys 4
- Aspect ratio 2 and number of storeys 7
- Aspect ratio 2 and number of storeys 10
- Aspect ratio 3 and number of storeys 4
- Aspect ratio 3 and number of storeys 7
- Aspect ratio 3 and number of storeys 10

Table -1: Properties of The Building Selected for The Study

Type of building	Symmetrical office building
Zone	IV
Number of floors	G+3 floors, G+6 floors & G+9 floors
Typical storey height	3.5m
Ground floor height	3.5m
Live Load	1.5 kN/m^2 for roof 3 kN/m^2 for typical floors
Grade of concrete	M25
Grade of steel	Fe415
Thickness of brick wall	230mm
Density of concrete	25 kN/m^3
Response reduction factor	3
Importance factor	1
Beam dimension	350 x 600mm
Column dimension	450 x 450 mm
Thickness of slab	120mm

4. CALCULATION OF FLEXIBILITY INDEX

To classify diaphragms as rigid, semi-rigid, semi-flexible or flexible in a practical way equations are needed. Therefore, two simple equations that have been previously proposed in the literature were evaluated to assess the diaphragm flexibility. Both formulations are based on the lateral displacements for the floor systems [1].

The flexibility index proposed in US recommendations and codes such as UBC-97 or FEMA-368 is perhaps the most widely known worldwide. According to this index, the diaphragm is considered flexible when the maximum lateral deformation of the diaphragm is more than two times the average story drift of the associated story. Otherwise, it may be considered rigid for practical purposes. This index is very helpful to identify truly flexible diaphragms, but neglect the semi-flexible or semi-rigid condition therefore, it is not useful to classify the floor systems under study [1].

In 1999 Ju and Lin proposed a flexibility stiffness index which is useful to classify the floor systems under study. To compute the flexibility index R two lateral displacements are required: (a) the peak lateral displacement at the center of the floor system that was modelled to assess any potential flexibility ($\Delta_{flexible}$) and (b) the peak lateral displacement at the center of the floor system modelled as a rigid diaphragm (Δ_{rigid}). Therefore, Ju and Lin R flexibility index is computed as: $R=\frac{\Delta_{flexible}-\Delta_{rigid}}{\Delta_{flexible}}$

For the buildings, a practical preliminary classification could be: (a) R ≤ 0.25for a rigid diaphragm, (b) 0.25< R ≤ 0.35 for a semi-rigid diaphragm, (c) 0.35< R ≤ 0.45 for a semi-flexible diaphragm, and (d) R > 0.45 for a flexible diaphragm [7].

5. RESULTS AND DISCUSSIONS

Results are obtained from the building models and compared in the form of

- Storey displacement
- Base shear reaction

A. Storey displacement of the buildings with waffle floor system

Table-2 represent the maximum storey displacement values for static analysis of the building with different aspect ratio and waffle floor system considering the seismic force. The storey displacement when it is subjected to load combination of dead load and earthquake load is taken into account. Table-3 represent the maximum storey displacement values for the dynamic analysis of the building; with different aspect ratio and waffle floor system considering the seismic force. Table-4 represent the storey displacement for the building with waffle floor system considering the wind force.

Table -2: Storey Displacement for Linear Static Analysis of A Waffle Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	27.52	63.74	99.23
2	26.05	62.08	93.85
3	37.04	71.98	124.92

Table-3: Storey Displacement for Dynamic Analysis of A Waffle Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	369.19	690.64	1489.12
2	340.78	679.21	1370.09
3	483.18	946.18	1758.54

Table-4: Storey Displacement for Wind Force For Waffle Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	4.55	17.94	35.41
2	4.12	14.52	32.36
3	7.52	27.19	71.46

It is obtained that the storey displacement increases as the number of stories increases; for both static and dynamic analysis. Also, the storey displacement values are more in the case of dynamic analysis compared to that of static analysis for the building. The storey displacement values are smaller for aspect ratio 2 compared to that for aspect ratio 1. The decrease in value of the storey displacement may be due to the baywidths considered. The storey displacement values are higher for aspect ratio 3 than that obtained for the aspect ratio 1 and aspect ratio 2. As the aspect ratio increases, there is an increase in storey displacement values with respect to the bay width of the building. As the number of stories increases the storey displacement increases for all the aspect ratios considered. From the results obtained for both the static and dynamic analysis, it can be concluded that the pattern of the increase in storey displacement values is same. From Table-4 it is obtained that the storey displacement increases as the number of stories increases considering the wind force. Higher values are obtained for building with aspect ratio 3.

Table-5: Storey Displacement for Different Aspect Ratio with Diaphragm for Waffle Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	25.71	46.79	70.98
2	17.55	45.81	66.59
3	27.13	50.04	80.18

Table-5 represent the storey displacement values for the building with respect to aspect ratio for the waffle floor system. The storey displacement when it is subjected to load combination of dead load and earthquake load is taken into account. From the results, it is obtained that the storey displacement increases as the number of storeys increase for both with and without diaphragm condition.

It is obtained that the storey displacement values are more in the case of the ten storey buildings and also the storey displacement values are more in the case of building with aspect ratio 3. The storey displacement values are more in the case of the building without diaphragm condition for all the aspect ratios considered.

Table- 6: Classification of Diaphragm Condition for Waffle Floor System

Aspect Ratio	Number of Storeys	R	Classification
1	4	0.065	Rigid
	7	0.266	Semi Rigid
	10	0.285	Semi Rigid
2	4	0.326	Semi Rigid
	7	0.168	Semi Rigid
	10	0.304	Semi Rigid
3	4	0.268	Semi Rigid
	7	0.304	Semi Rigid
	10	0.36	Semi Flexible

Table-6 represent the classification of waffle floor system with respect to the diaphragm conditions. As the number of storeys increase there is a change in diaphragm condition considering all the aspect ratios. As the aspect ratio increases the diaphragm condition changes from rigid to semiflexible, therefore, the building with aspect ratio 1 is better as compared to other aspect ratios since the rigid condition is better. Suitable design procedures are needed to be considered for the higher aspect ratios as there is a change in diaphragm conditions. Table-7 represent the base shear reaction for the building with waffle floor system.

Table-7: Base Shear Reaction of Waffle Floor System

Aspect Ratio	Number of Storeys	Base Shear(kN)
1	4	1268.36
	7	1486.16
	10	1617.58
2	4	1166.4
	7	1375.70
	10	1543.01
3	4	1472.2
	7	1705.79
	10	1979.11

B. Storey displacement of the buildings with ribbed floor system

Table-8 represent the maximum storey displacement values for static analysis of the building with different aspect ratio and ribbed floor system considering the seismic force. The storey displacement when it is subjected to load combination of dead load and earthquake load is taken into account. Table-9 represent the maximum storey displacement values for the dynamic analysis of the building; with different aspect ratio and ribbed floor system considering the seismic force.Table-10 represent the storey displacement for the building with ribbed floor system considering the wind force.

Table-8: Storey Displacement For Linear Static Analysis of A Ribbed Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	22.73	42.95	57.8
2	16.698	36.28	53.61
3	24.09	62.79	87.73

Table-9: Storey Displacement For Dynamic Analysis of A Ribbed Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	311.605	559.75	713.23
2	206.02	528.38	675.87
3	337.31	573.85	946.6

Table-10: Storey Displacement for Wind Force for Ribbed Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	4.47	15.398	25.83
2	2.82	12.53	22.73
3	7.21	24.67	56.29

It is obtained that the storey displacement increases as the number of stories increases; for both static and dynamic analysis. Also, the storey displacement values are more in the case of dynamic analysis compared to that of static analysis for the building. The storey displacement values are smaller for aspect ratio 2 compared to that for aspect ratio 1. The decrease in value of the storey displacement may be due to the baywidths considered. The storey displacement values are higher for aspect ratio 3 than that obtained for the aspect ratio 1 and aspect ratio 2. As the aspect ratio increases, there is an increase in storey displacement values with respect to the bay width of the building. As the number of stories increases the storey displacement increases for all the aspect ratios considered. From the results obtained for both the static and dynamic analysis, it can be concluded that the pattern of the increase in storey displacement values is same.From Table-10 it is obtained that the storey displacement increases as the number of stories increases considering the wind force. Higher values are obtained for building with aspect ratio 3.The displacement values are smaller than that obtained from the waffle floor system for the ribbed floor system.

Table-11: Storey Displacement for Different Aspect Ratio with Diaphragm for Ribbed Floor System

Aspect Ratio	Storey Displacement(mm)		
	4 Storey	7 Storey	10 Storey
1	19.81	38.46	54.75
2	15.64	30.39	48.49
3	23.91	45.71	57.16

Table-11 represent the storey displacement values for the building with respect to aspect ratio for the ribbed floor system. The storey displacement when it is subjected to load combination of dead load and earthquake load is taken into account. From the results, it is obtained that the storey displacement increases as the number of storeys increase for both with and without diaphragm condition for the ribbed floor system.

It is obtained that the storey displacement values are more in the case of the ten storey buildings and also the storey displacement values are more in the case of building with aspect ratio 3 for the ribbed floor system. The storey displacement values are more in the case of the building without diaphragm condition for all the aspect ratios considered. The storey displacement values are smaller than that compared to waffle floor system.

Table-12 Classification of Diaphragm Condition for Ribbed Floor System

Aspect Ratio	Number of Storeys	R	Classification
1	4	0.11	Rigid
	7	0.105	Rigid
	10	0.053	Rigid
2	4	0.003	Rigid
	7	0.09	Rigid
	10	0.25	Rigid
3	4	0.007	Rigid
	7	0.27	Semi Rigid
	10	0.34	Semi Rigid

Table-12 represent the classification of ribbed floor system with respect to the diaphragm conditions. For the classification, the values of with and without diaphragm condition from the static analysis for different aspect ratios and storey heights are considered. The values of with diaphragm denote the building modelled in the assumption of being rigid. As the number of stories increases, there is a change in the diaphragm condition considering all the aspect ratios. For the aspect ratio 1 and aspect ratio 2 the diaphragm condition is same for all the stories considered. Therefore, the building with aspect ratio 1 and aspect ratio 2 are better compared to that of the aspect ratio 3. Suitable design procedures are needed to be considered for the higher aspect ratios as there is a change in the diaphragm conditions. Table-13 represent the base shear reaction for the building with ribbed floor system.

Table-13: Base Shear Reaction of Waffle Floor System

Aspect Ratio	Number of Storeys	Base Shear(kN)
1	4	1123.03
	7	1329.34
	10	1451.59
2	4	942.28
	7	1116.75
	10	1220.911
3	4	1316.79
	7	1557.73
	10	1701.805

C. Storey displacement of the buildings with ordinary floor system

Table-14 represent the maximum storey displacement values for static analysis of the building with different aspect ratio and ordinary floor system considering the seismic force. The storey displacement when it is subjected to load combination of dead load and earthquake load is taken into account. Table-15 represent the maximum storey displacement values for the dynamic analysis of the building; with different aspect ratio and ordinary floor system considering the seismic force.The storey displacement values are larger than the ribbed floor system and smaller than the ribbed floor system. Table-16 represent the maximum storey displacement values for static analysis of the building with respect to the aspect ratio for the ribbed, ordinary and waffle floor systemThe storey displacement when it is subjected to load combination of dead load and earthquake load is taken into account. From the Chart-1, it is obtained that the storey displacement increases as the number of stories increases. The storey displacement values are larger for the waffle floor system compared to that of the ribbed and ordinary slab system. So it not advisable to use the waffle floor system for higher storey heights.

Table-14: Storey Displacement for Linear Static Analysis of A Ordinary Floor System

Aspect Ratio	Number of Storeys	Storey Displacement(mm)
1	4	25.47
	7	50.42
	10	71.19
2	4	23.95
	7	62.67
	10	92.13
3	4	26.85
	7	69.77
	10	120.45

Table-15: Storey Displacement for Dynamic Analysis of A Ordinary Floor System

Aspect Ratio	Number of Storeys	Storey Displacement(mm)
1	4	347.63
	7	781.69
	10	1107.15
2	4	332.61
	7	687.07
	10	1084.74
3	4	387.04
	7	901.09
	10	1445.27

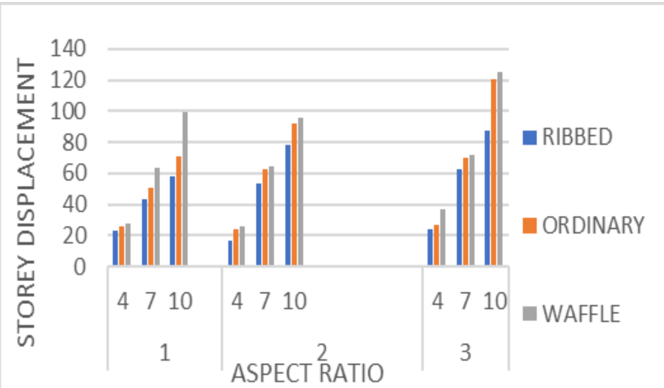

Chart-1: Storey displacement graph of building with ribbed, ordinary and waffle floor system

Table-16: Comparison of Ribbed, Ordinary and Waffle Floor System

Aspect Ratio	Number of Storeys	Storey Displacement(mm)		
		Ribbed	Ordinary	Waffle
1	4	22.73	25.47	27.52
	7	42.95	50.42	63.74
	10	57.8	71.19	99.23
2	4	16.698	23.95	26.05
	7	53.45	62.67	64.09
	10	77.86	92.13	95.74
3	4	24.09	26.85	37.04
	7	62.07	69.77	71.98
	10	87.73	120.45	124.92

6. CONCLUSIONS

The study is conducted to define the diaphragm condition for the buildings with different floor systems. The selected floor systems are ribbed RC slabs and RC waffle flat slabs. All the models are analysed under uniformly distributed lateral loads. To assess the behaviour of the different floor systems as diaphragms (rigid, semi-rigid, semi-flexible or flexible), the peak lateral displacement for the building are considered.

- The study of diaphragm condition is important in order to help improve professional practice and help reduce the vulnerability of the new inventory of structures
- The seismic performance of the ribbed slab system was better than the waffle slab system considering the maximum storey displacement for both static and dynamic analysis. For both the static and dynamic analysis the maximum storey displacement increases linearly.
- For the waffle floor system, the diaphragm condition changes as the aspect ratio increases. As the aspect ratio increases the diaphragm condition changes from rigid to semi-flexible therefore, the building with aspect ratio 1 is better as compared to other aspect ratios since the rigid condition is better.
- For the ribbed floor system, there is less change in the diaphragm condition as the aspect ratio increases. As the aspect ratio increases the diaphragm condition changes from rigid to semi-rigid condition only therefore, the building with aspect ratio 1 and 2 is better as compared to other aspect ratios.
- The storey displacement values are more in the case of the buildings with waffle floor system, compared

to that of the ribbed and ordinary floor system. Therefore, it is not advisable to use the waffle floor system as the storey height increases.

- As the aspect ratio increases, there is a change in diaphragm condition for both the ribbed and waffle floor system and the aspect ratio 1 and 2 shows better performances under seismic conditions.
- For the waffle floor system, the diaphragm condition changes as the height increases. The buildings with smaller heights show better diaphragm condition.
- For the ribbed floor system, there is less change in the diaphragm condition as the height increases.

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